Chapter Two

Atmospheric Observations

2.1 Overview

C.D. Keeling of the Scripps Institution of Oceanography was the first to make regular measurements of atmospheric CO_2 concentrations in 1958, at Mauna Loa (Fig. 2-1), Antarctica, and La Jolla (Keeling, 1960). Among other things, these measurements revealed a steady increase in atmospheric CO_2 approximately equal to half the rate of CO_2 emissions from human activities (Keeling *et al.*, 1989a). This removal of anthropogenic CO_2 from the atmosphere and its causes have significant consequences for future CO_2 and climate trends, and remain a very active area of research today. The Scripps CO_2 measurements continue through a global network of about 10 sites, and they have been complemented by the efforts of other U.S. and international laboratories. Most notably, the Cooperative Air Sampling Network of NOAA's Climate Monitoring and Diagnostics Laboratory (CMDL), which began in the late 1960s (Komhyr *et al.*, 1985), now includes over 60 sites around the globe (Fig. 2-2).

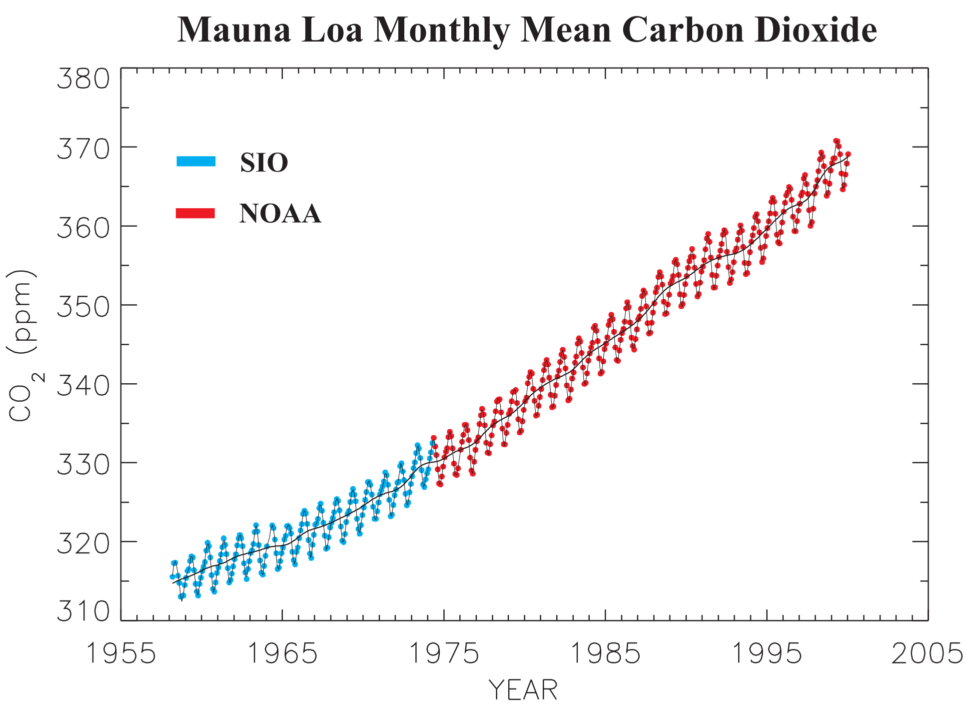

Figure 2-1: Atmospheric carbon dioxide monthly mean mixing ratios. Data prior to May 1974 are from the Scripps Institution of Oceanography, data since May 1974 are from the National Oceanic and Atmospheric Administration. A long-term trend curve is fitted to the monthly mean values.

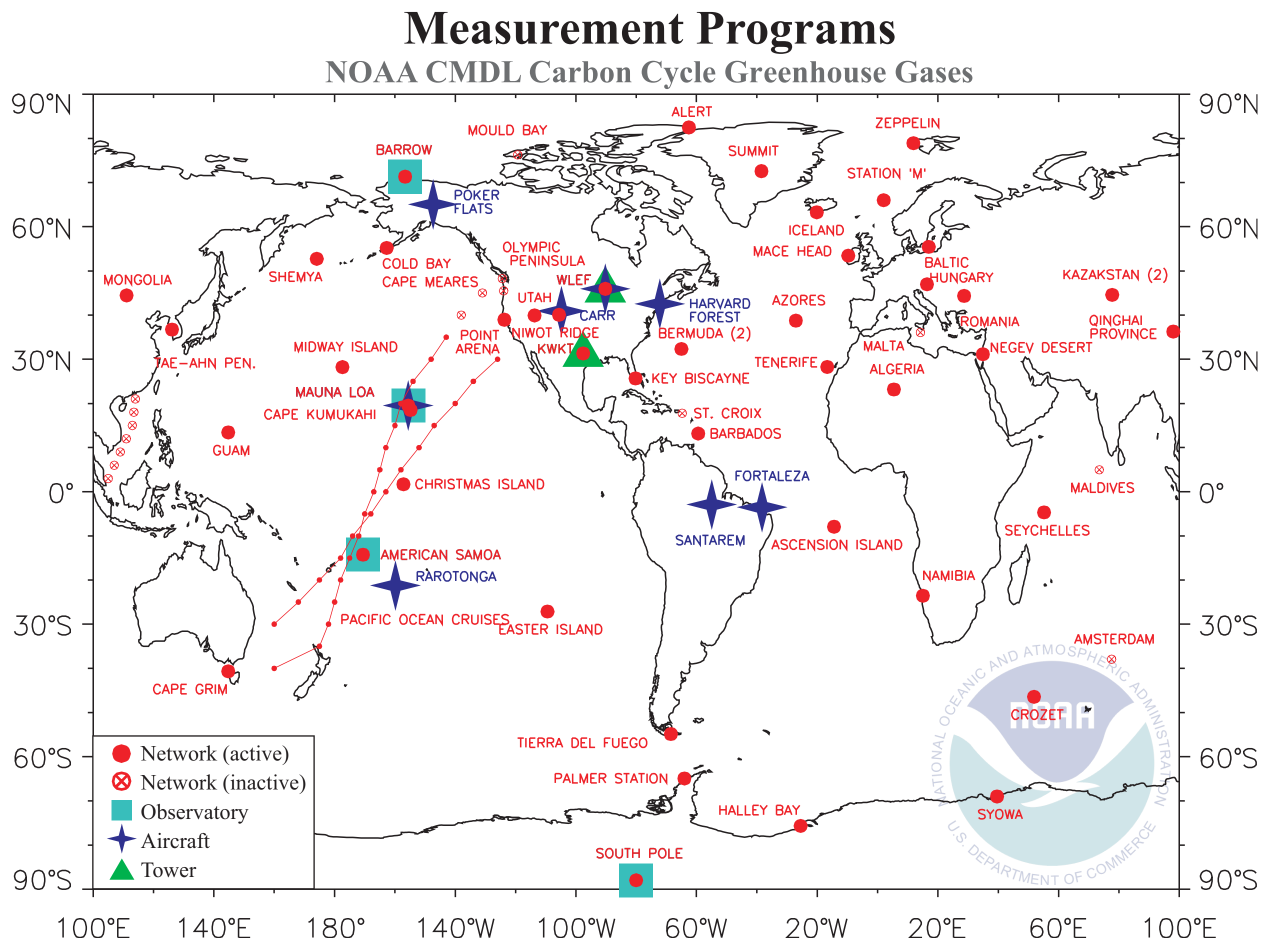

Figure 2-2: The NOAA CMDL Carbon Cycle Greenhouse Gases group operates four measurement programs. In situ measurements are made at the CMDL baseline observatories: Barrow, Alaska; Mauna Loa, Hawaii; Tutuila, American Samoa; and South Pole, Antarctica. The cooperative air-sampling network includes samples from fixed sites and commercial ships. Measurements from tall towers and aircraft began in 1992. Presently atmospheric carbon dioxide, methane, carbon monoxide, hydrogen, nitrous oxide, sulfur hexaflouride, and the stable isotopes of carbon dioxide and methane are measured.

By comparing CO_2 concentrations in the Northern and Southern Hemispheres, it appears that much of the anthropogenic CO_2 uptake must be occurring in northern mid-latitudes (Keeling *et al.*, 1989b) and that this uptake is likely a result of terrestrial processes (Tans *et al.*, 1990). Additional measurements of $^{13}C/^{12}C$ ratios in CO_2 (Keeling *et al.*, 1989a; Ciais *et al.*, 1995) and of O_2/N_2 ratios (Keeling and Shertz, 1992; Bender *et al.*, 1996) provide valuable constraints on the land-ocean partitioning of CO_2 uptake and the causes of seasonal to interannual variations in the CO_2 growth rate (Fig. 2-1) (Battle *et al.*, 2000).

Despite the significant advances to date, we must go still further in quantifying spatial and temporal variations in air-sea and air-land CO_2 fluxes, and identifying their controlling biogeochemical processes. This process-level understanding will be critical to resolving the relationships between atmospheric CO_2 and climate change, and to predicting future atmospheric CO_2

levels and climate. Atmospheric observations of CO_2, $^{13}C/^{12}C$ ratios in CO_2, and O_2/N_2 ratios will clearly continue to play a vital role in determining and predicting the fate of human-emitted CO_2. Measurements of additional atmospheric species should also be included in any attempt to understand the global carbon cycle. For example, $^{18}O/^{16}O$ ratios in CO_2 constrain gross rates of terrestrial exchange, and concentrations of CH_4 and N_2O are radiatively important and linked to terrestrial processes that also affect CO_2. Measurements of industrial tracers (e.g., CO, SF_6, $^{14}C/^{12}C$ ratios in CO_2), terrestrial tracers (e.g., ^{222}Rn), and oceanic tracers (e.g., Ar/N_2, O_2/N_2) will also be important in investigating atmospheric transport and validating fluxes calculated from inverse models. The recommendations in this report directly concern implementation of the oceanic and atmospheric components of the recently formulated U.S. Carbon Cycle Science Plan (CCSP, 1999). The CCSP and other documents provide additional background information on natural and anthropogenic effects on atmospheric CO_2 and their relationships to other atmospheric species (IPCC, 1996; CCSP, 1999; IPCC, 2001).

This chapter outlines and justifies specific research recommendations for the next decade that will ultimately result in a comprehensive atmospheric observing system for the global carbon cycle. To make this task tractable, we have divided our recommendations into two time horizons: 1 to 5 years, and 6 to 10 years. Because research directions in the second period depend on what we expect to learn in the first, we have focused our discussion and specific recommendations on the timescale of 1 to 5 years. For the timescale of 6 to 10 years, we make more general recommendations that will be adaptable according to the knowledge gained and technical and computational advances made in the interim.

The complexity of atmospheric mixing and CO_2 source and sink processes necessitates the use of sophisticated numerical models in interpreting observations and making predictions based on them. However, it is clear that existing atmospheric transport models (ATMs) are insufficient for this task (Gloor *et al.*, 2000). While the amount of background data is a fundamental limitation in these calculations, the models themselves are too coarse to use much of the information contained in existing measurements, and models also have large uncertainties in their representations of vertical transport. The modeling results we present in support of our recommendations below should not be misinterpreted as an endorsement of current models or inverse methods. Our approach with respect to existing and future models has several facets: (1) we anticipate significant modeling improvements in resolution, boundary-layer parameterization, and coupling to underlying process models in the next decade; (2) we conduct network design studies using existing ATMs to make our best estimate of what observations will be most useful in constraining regional CO_2 fluxes in conjunction with future models; and (3) we recommend specific observations that will challenge and support improvement in existing models.

2.1.1 The atmospheric observing system one decade from today

Our primary goal for the coming decade of atmospheric carbon cycle measurements is to build the U.S. contribution to sustained global observations that can accurately measure net CO_2 sources and sinks, natural and human, from large regions. Climate variations (IPCC, 1996), terrestrial ecosystem responses (Myneni *et al.*, 1997), and ocean CO_2 flux patterns (Takahashi *et al.*, 1997) are each reasonably coherent on a 1,000 km scale. For this reason, regional flux determinations will help achieve a quantitative understanding of processes controlling CO_2 fluxes between the atmosphere, oceans, and land biosphere. This knowledge is an important prerequisite for sound predictions of the carbon cycle's future behavior in response to natural and human perturbations. Regional-scale flux estimates will also help to bridge the current gap between local process-oriented studies and global constraints. Taking land use as an example, widespread regrowth of forests in the eastern half of the United States, as well as woody encroachment on grassland ecosystems in the southwest, should leave a measurable signature on atmospheric CO_2. Our future observing system should have the following characteristics:

- Regional spatial resolution, down to 10^6 km^2 on the continents and 10^7 km^2 over the oceans, with an accuracy of 0.1 Gt C/yr. This resolution will enable meaningful quantification of processes regulating surface carbon exchange. An ability to see the effects on atmospheric CO_2 of specific processes and mechanisms on these spatial scales will allow a marked increase of confidence in our understanding and predictive capability.

- Integration of satellite observations. The in situ measurements should be able to stand on their own, but will be merged with satellite CO_2 data if and when these become available, providing crucial accuracy to the latter. Space-based observations of the CO_2 mole fraction in the atmospheric column are expected to have nearly complete spatial coverage, but lower chemical resolution and accuracy.

- Assimilation of all available data. Data assimilation models must be an integral part of the observing system. The models should assimilate weather and CO_2 observations, and remotely sensed indicators of primary productivity. They should be high resolution in time and space, dynamically consistent, and include carbon processes.

2.1.2 Goals for the next 5 years

As a necessary step toward developing this observing system, we have set more immediate goals for the next 5 years. These goals are to measure the annual CO_2 flux between the temperate North American biosphere and the atmosphere to an accuracy of 0.2 Gt C/yr, while resolving the rest of the globe's continental regions to 0.5 Gt C/yr, and determining air-sea fluxes for major ocean regions to 0.1–0.2 Gt C/yr. A number of approaches show promise for achieving these goals in the near future:

- Calculation of CO_2 fluxes between surface regions and the atmosphere by direct inversion of atmospheric CO_2 data using ATMs, complemented by $^{13}C/^{12}C$ and O_2/N_2 observations (e.g., Gloor *et al.*, 2000; Fan *et al.*, 1998; Tans *et al.*, 1990; Keeling *et al.*, 1989b; see discussion below).

- Sea surface pCO_2 measurements synthesized with an ocean model and converted to fluxes using a gas-exchange parameterization (e.g., Takahashi *et al.*, 1997; see Chapter 3 of this report).

- Forward predictions or inverse calculations using biogeochemical ocean general circulation models (BOGCMs), constrained by observations of oceanic carbon, nutrients, oxygen, ^{13}C, and atmospheric O_2/N_2 (e.g., Murnane *et al.*, 1999; Gruber *et al.*, 1998; Quay *et al.*, 1992; Stephens *et al.*, 1998; see Chapter 4).

- Satellite observations of NDVI, land-use histories, tower eddy flux measurements, and forest and soil carbon inventories synthesized with terrestrial ecosystem models (TEMs) that link air-land CO_2 fluxes to terrestrial processes (e.g., Myneni *et al.*, 1997; Wofsy *et al.*, 1993; Schimel *et al.*, 2000; this research area is not a focus of report).

In the context of these broad approaches, atmospheric observations can contribute significantly to CO_2 flux estimates by providing the essential data required by inverse calculations, and by providing data to validate and improve ATMs, BOGCMs, and TEMs. With improvements to ATM boundary layer parameterizations, the existing network of atmospheric CO_2 monitoring stations (Fig. 2-2) will be sufficient to constrain surface fluxes on the scale of broad (20°–30°) latitudinal zones. In addition, atmospheric measurements of O_2/N_2 and $^{13}C/^{12}C$ will provide information on the terrestrial versus oceanic partitioning of these fluxes. Refining these atmospheric constraints to specific continental-scale areas, and in particular discriminating between fluxes from different regions at the same latitude, will require improved data quality, improved ATMs, and significant increases in data coverage.

Temperate North America is an important region for study of the terrestrial carbon cycle, because it is a potentially large sink for anthropogenic CO_2 (Fan *et al.*, 1998). Detailed knowledge of its ecosystems, soils, hydrology, past and present land use, and climate trends exist, allowing more robust modeling and analysis than in other regions. North America is also the natural region of focus for U.S.-led research. Furthermore, as the United States is currently the largest national CO_2 emitter, the region could provide a testing ground for the development of methods to measure the magnitude of fossil CO_2 emissions. We expect that initially focusing on one continental-scale region will greatly improve our chances for short-term success, and for learning how to extend similar coverage most efficiently to the entire globe.

In the next section and Addendum 2-1, we review the current status of atmospheric observations related to the carbon cycle. In the following section, we discuss the current limitations to atmospheric inverse calculations, and in Addendum 2-2 we use several ATMs to quantitatively estimate the specific atmospheric observations, model improvements, and additional constraints required to achieve our stated 5-year goals. These analyses indicate the need for several advances: (1) additional background CO_2 measurements in specific locations primarily over the continents, (2) improvements to other global and regional constraints on the carbon cycle, (3) improved maintenance by individual laboratories of their calibration scale as well as ongoing tight comparisons of measurements between laboratories, and (4) improvements in the ATMs themselves. The potential biases and required measurement accuracy also point to the need for developing robust continuous CO_2 analyzers that allow calibrated measurements in the field. These analyzers would complement flask samples and could be used to take advantage of existing commercial ship and aircraft platforms. Finally, at the end of this chapter, we outline specific recommendations for enhanced atmospheric observations. While the scope of this chapter is restricted to the establishment of a sustained atmospheric observing system, we have indicated links to other activities needed to improve our understanding of the carbon cycle.

2.2 Background

2.2.1 Current status of atmospheric observations

Detecting regional- to continental-scale sources and sinks requires that the individual CO_2 concentration measurements have a certain level of consistency. As we show below by comparison to expected flux signals, this level is $\leq$0.1 ppm, in agreement with the internationally recognized goal set by the World Meteorological Organization (WMO) in 1981 (WMO, 1981). The accuracy of today's measurements is generally not better than $\pm$0.2 ppm, despite the fact that short-term precision or repeatability is often substantially better at about 0.05 ppm. Two measurement components are important to attaining accuracy. The first is the maintenance of a reference scale linked to primary quantities, along with the active maintenance of traceability to that scale by every laboratory. Second, the systematic biases associated with sampling and measurement methodology must be eliminated, by means of a very significant ongoing effort. The maintenance of traceability has been tested during the last decade by several "round robin" comparisons, in which sets of circulating high-pressure gas mixtures have been measured by more than 20 laboratories. The average standard deviation has been 0.15 ppm or greater (Globalview-CO_2, 2000), already short of the WMO goal. Measurement biases due to sampling, materials, gas-handling, instruments, and measurement protocols are added independently to the uncertainty of the calibration gases used. We present a discussion of such biases in Addendum 2-1.

Natural and anthropogenic CO_2 fluxes are inextricably linked to fluxes of other gases and tracers, such as O_2, CO, CH_4, N_2O, SF_6, and $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios in CO_2. These linkages provide valuable opportunities to investigate CO_2 fluxes through related measurements. For example, measurements of $^{13}C/^{12}C$ ratios can distinguish contributions to CO_2 variations and fluxes from oceanic versus terrestrial (e.g., Ciais *et al.*, 1995; Battle *et al.*,

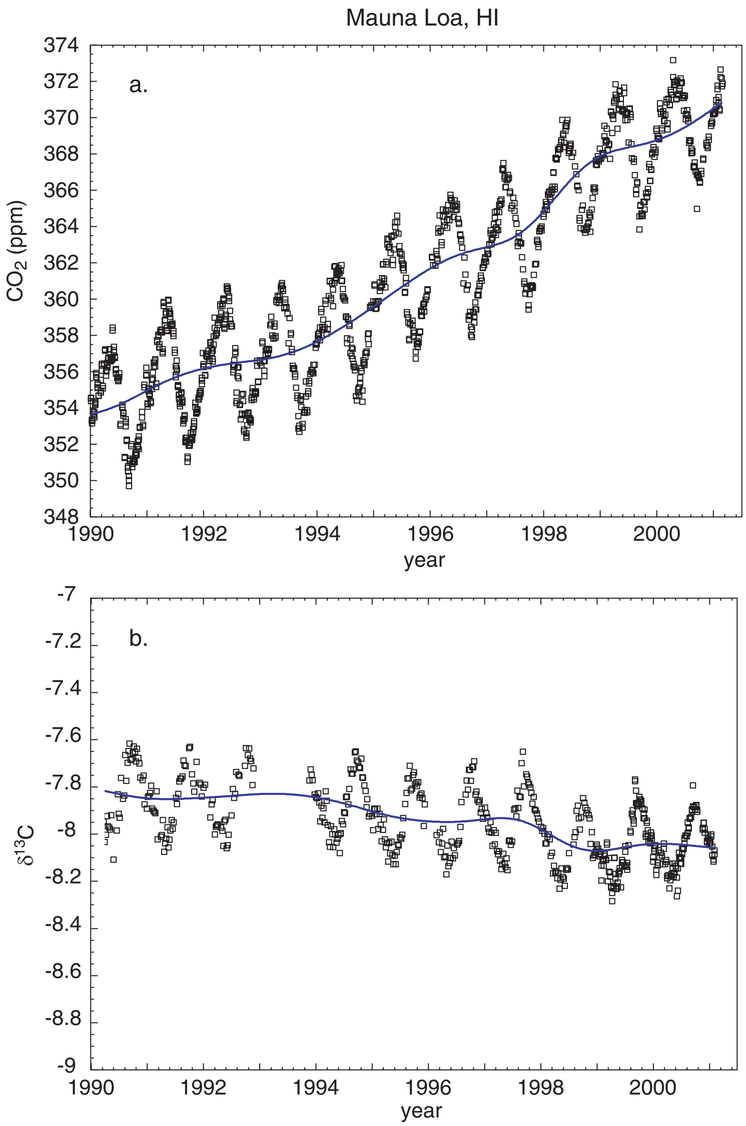

Figure 2-3: CO_2 and $^{13}C/^{12}C$ ratios measured by CMDL in air sampled at Mauna Loa. The decrease in CO_2 growth rate in 1997 combined with the corresponding decrease in the rate of $^{13}C/^{12}C$ decline is indicative of greater uptake by the land biosphere (Battle *et al.*, 2000).

2000), and C-3 versus C-4 photosynthetic processes (Farquhar *et al.*, 1989) (Fig. 2-3). This is made possible by the preferential uptake of ^{12}C relative to ^{13}C during C-3 photosynthesis, and the relatively smaller discriminations during C-4 photosynthesis and oceanic exchange. Isotopic measurements are difficult and even more prone to the type of systematic biases discussed for CO_2 concentration measurements in Addendum 2-1. Ongoing interlaboratory comparisons indicate that current agreement is typically no better than 0.02 permil, and occasionally worse than 0.05 permil. These offsets are still quite large relative to the recognized international goal of 0.01 permil (Allison *et al.*, 1995). Improvements to these measurements will lead directly to improvements in the value of the $^{13}C/^{12}C$ constraints on carbon cycling.

Recent measurements of atmospheric O_2 concentrations (expressed as O_2/N_2 ratios) have also led to new insights into the carbon cycle that were not possible through measurements of CO_2 alone. Most significantly, the detection of interannual trends in O_2 (Fig. 2-4) has allowed the separate calculation of global oceanic and terrestrial sinks for anthropogenic carbon (e.g., Keeling and Shertz, 1992; Bender *et al.*, 1996; Keeling *et al.*, 1996b). This constraint is made possible by the tight link between CO_2 and O_2 during terrestrial photosynthesis and respiration, and the lack of any O_2 release associated with the oceanic uptake of anthropogenic CO_2. In addition, measurements of seasonal cycles in atmospheric O_2 have provided hemispheric estimates of oceanic biological productivity (Keeling and Shertz, 1992; Bender *et al.*, 1996) and air-sea gas exchange (Keeling *et al.*, 1998). Observed latitudinal variations in atmospheric O_2 constrain the southward transport of O_2 and CO_2 in the oceans (Keeling *et al.*, 1996b), and have been used to test the performance of global ocean carbon cycle models (Stephens *et al.*, 1998). Because of the high level of relative precision, measurements of O_2/N_2 are even more susceptible to systematic errors than are measurements of CO_2 and ^{13}C. Interlaboratory comparisons for O_2/N_2 are currently not sufficient. Furthermore, additional work on the effects of various gas-handling methods can improve the measurements considerably.

CO_2 observations from 18 laboratories, at 65 fixed surface sites, three towers, three regular vertical profiles from aircraft, and two repeated ship transects are included in the current release of the Globalview database (Globalview-CO_2, 2000). A substantial number of existing observations have still not been included, in some cases because the records are very short, but more often because the laboratory responsible for the data does not participate in the effort to make data widely available in a global context. Measurements of $^{13}C/^{12}C$ and O_2/N_2 ratios are also made by multiple laboratories on somewhat smaller networks, but it has not yet been possible to combine measurements of these quantities from different groups into consistent data sets.

Atmospheric observations have led to some important discoveries in recent years. Figure 2-5 shows the surface interhemispheric CO_2 gradient due to fossil fuel burning alone, as modeled by 12 different transport models (Transcom 2 project, Law *et al.*, 1996). The average observed gradient from 1980 to 1990 is plotted as a thick black line. The discrepancies suggest a large net CO_2 sink at temperate latitudes in the Northern Hemisphere, a tropical source, and a sink at temperate southern latitudes. Combined with oceanic sink estimates based on CO_2 partial-pressure differences across the air-sea interface, this general picture has led to the hypothesis of a large terrestrial sink in the Northern Hemisphere (Tans *et al.*, 1990). The hypothesis has been supported by measurements of atmospheric oxygen (Keeling *et al.*, 1996b) and the $^{13}C/^{12}C$ ratio of CO_2 (Ciais *et al.*, 1995). The amplitude of the annual cycle of CO_2 has also increased significantly over the last few decades (Keeling *et al.*, 1996a). This change has been attributed to an earlier start of the growing season.

Currently, attempts are being made to interpret the observed east-west concentration difference between the North Atlantic and North Pacific basins

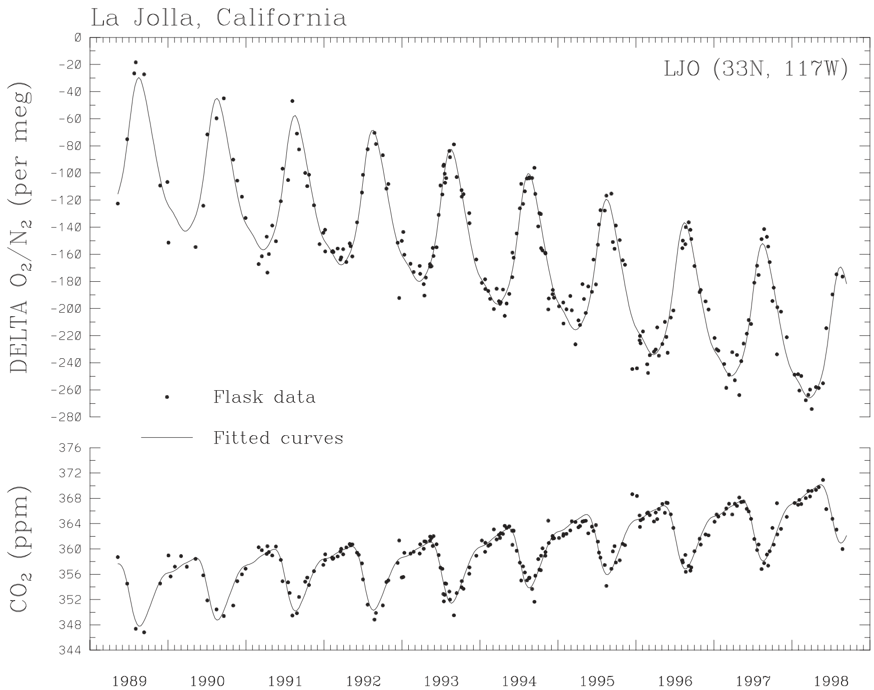

Figure 2-4: CO_2 and O_2/N_2 ratios measured by the Scripps O_2 Laboratory in air sampled at La Jolla. The vertical scales have been adjusted to be equivalent on a mole to mole basis. The greater rate of O_2/N_2 decline than CO_2 increase indicates that a significant amount of the industrial CO_2 emissions are being taken up by the oceans without a corresponding release of O_2 (Keeling *et al.*, 1996b).

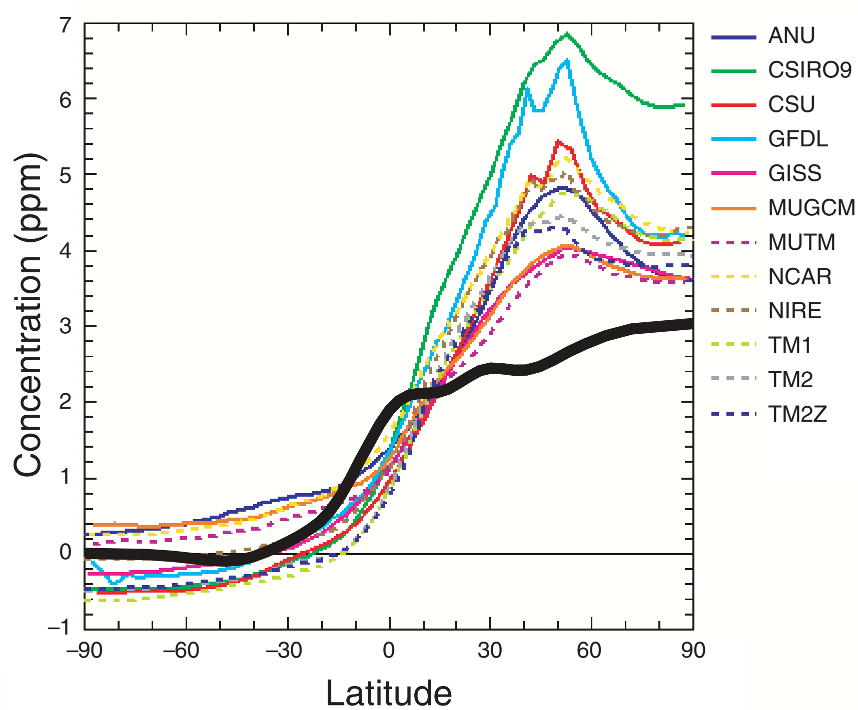

Figure 2-5: North-south zonal mean surface CO_2 concentration gradient resulting from fossil-fuel emissions, as modeled by 12 different atmospheric transport models (from Law *et al.*, 1996). The observed gradient from the CMDL network is shown as the thick black line.

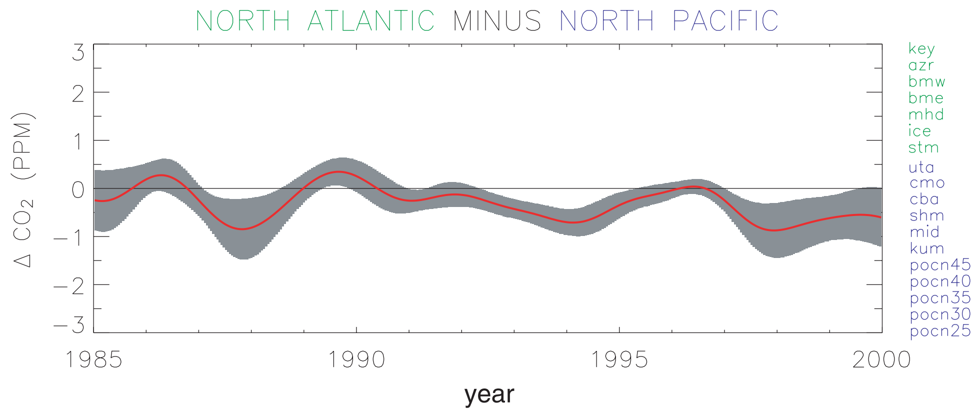

Figure 2-6: Annual-average atmospheric CO_2 concentration difference between the North Atlantic and the North Pacific basins, as observed at the CMDL network stations listed. The shaded band is an uncertainty estimate based on results using various subsets of these stations.

in terms of terrestrial and oceanic sources and sinks at these latitudes (Fig. 2-6). As discussed below, partitioning fluxes into various regions at similar latitudes will require better understanding of seasonal and diurnal mixing over the continents, in addition to the use of all available data. Sustained observations on very tall towers can be valuable in this respect. Measurements from towers in North Carolina and Wisconsin (Fig. 2-7a) (Bakwin *et al.*, 1998) show that the amplitude of the annual cycle over land is larger than, and that its phase leads, the annual cycle over the oceans. The continental boundary layer concentration also exhibits a strong and varying diurnal cycle superimposed on synoptic-scale variations (Fig. 2-7b) (Bakwin *et al.*, 1998).

2.2.2 Current limitations to inversions

A few simple calculations illustrate the strength of atmospheric CO_2 signals associated with various surface fluxes. Table 2-1 shows the magnitude of the rate of CO_2 change in the entire vertical column of air for several sources and sinks of interest. With a nominal measurement precision of 0.1 ppm, it is clear from Table 2-1 that emissions from Los Angeles should be very easy to measure. A 1 Gt C/yr sink distributed over the United States should also be detectable. If we assume a 5-day residence time for air over the United States, and that half the total column is mixed with surface air during this time, we estimate a signal in the lower atmosphere of $-0.08 \times 5 \times 2 = -0.8$ ppm for this postulated sink. This change in CO_2 mole fraction is comparable to the signals predicted by atmospheric transport models (ATMs) (Fig. 2-8a). This general relationship between flux and atmospheric surface signals of around 1 ppm /(Gt C/yr) for a continental-scale region, combined with the expected magnitudes of regional- to continental-scale fluxes, leads to our goal for interlaboratory agreement and measurement precision of 0.1 ppm or better.

Actual boundary layer signals will depend on the boundary layer thick-

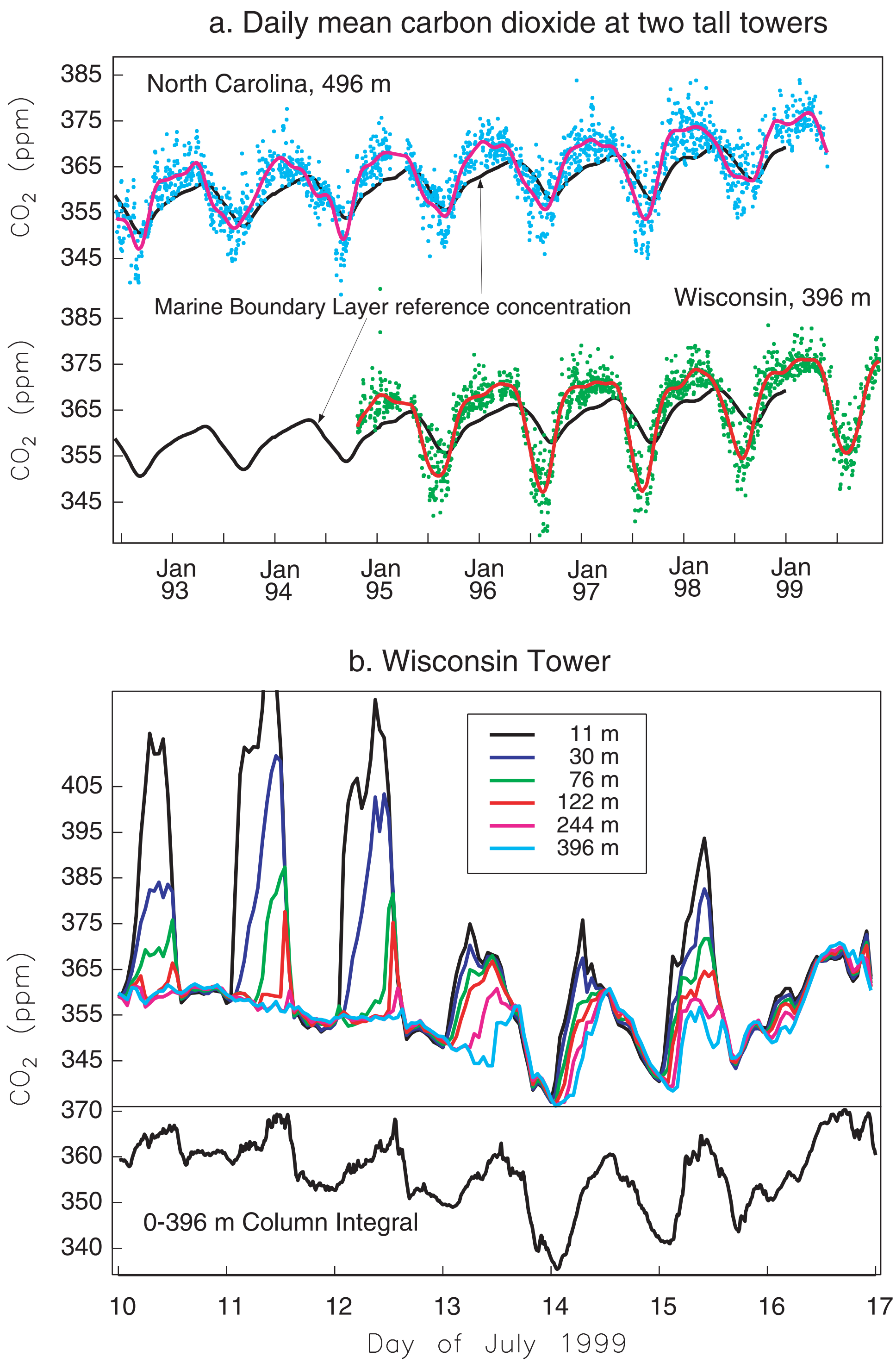

Figure 2-7: (a) Daily mean CO_2 mole fraction observed at two very tall towers. Also indicated are the simultaneous CO_2 trends observed over the oceans at the same latitudes as each tower. (b) One week of continuous CO_2 data collected from different heights on the WLEF transmitter tower in Wisconsin.

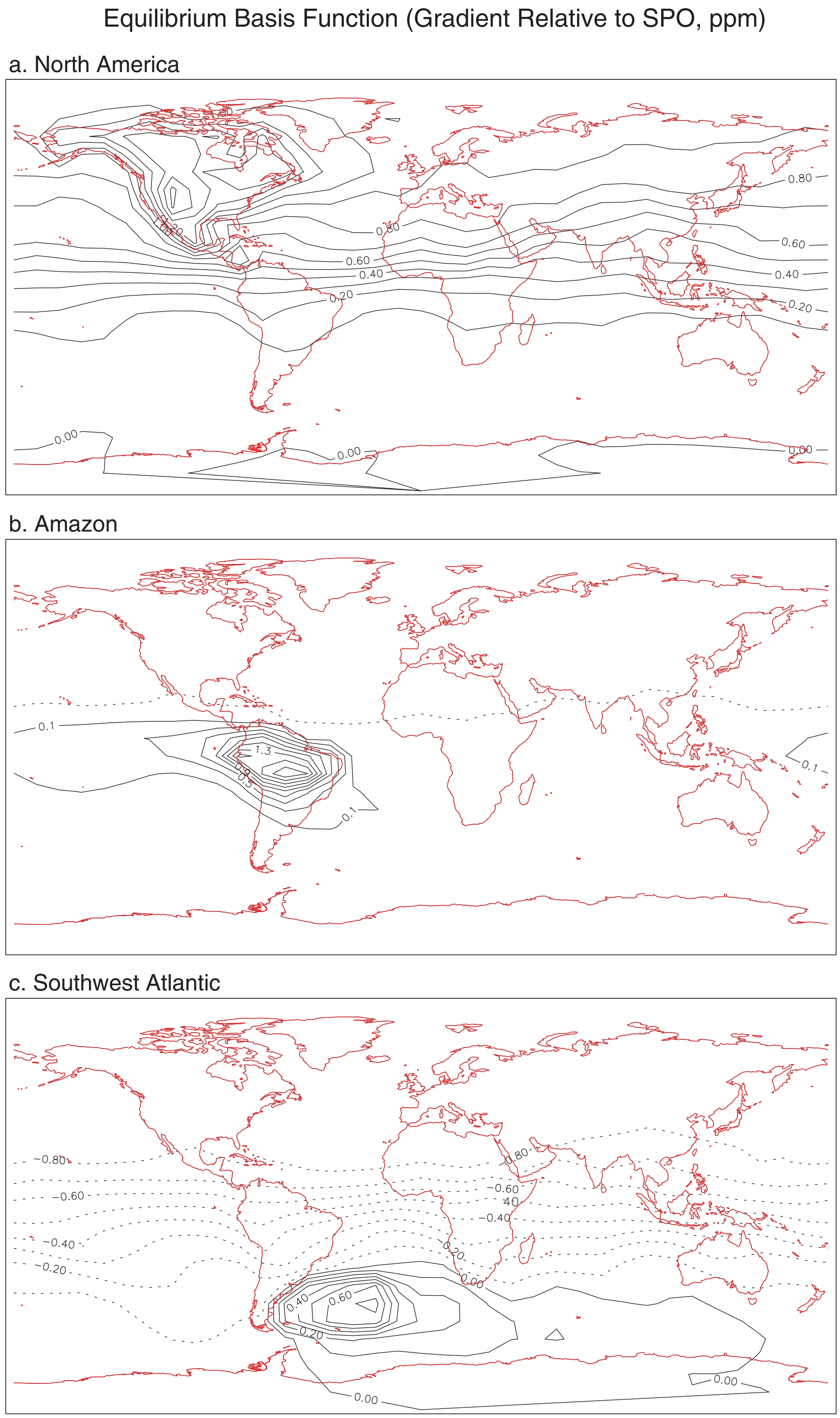

Figure 2-8: Equilibrium surface CO_2 concentrations ("footprints"), relative to the South Pole, calculated with the TM3 model for 1 Gt C/yr sources evenly distributed over (a) North America, (b) tropical South America, and (c) the western mid-latitude South Atlantic. The source in (c) corresponds to a region of significantly high chlorophyll and low pCO_2. Compare these signals to the locations of flask sites shown in Fig. 2-2.

ness, the rate of mixing with the free troposphere, and the residence time of air over the region. ATMs are thus needed to estimate the specific CO_2 concentration changes, as a function of time and place, resulting from a given surface flux. Conversely, ATMs can also be used to estimate surface fluxes from observed atmospheric CO_2 concentration changes. This approach is known as an atmospheric inverse calculation, or inversion. Sensitivity studies using ATMs show that the direct inversion of atmospheric CO_2 concentrations to obtain continental-scale fluxes is feasible. However, present uncertainties are large because of several factors: (1) limited CO_2 data relative to the dilution of signals by atmospheric mixing; (2) the coarse resolution of current inverse models, leading to the treatment of unresolved spatial and temporal variability as noise; and (3) systematic errors in ATMs. Focusing first on data sparseness, Gloor *et al.* (1999) investigated data requirements for calculating fluxes using existing models, assuming there were no errors in atmospheric transport. They found that resolving fluxes for 17 global regions to ± 0.2 Gt C/yr required a network of 150 randomly placed surface stations. This is approximately double the size of the current network.

The primary factor that leads to this high number of required stations is the mismatch in time and space between high-resolution variability in the CO_2 data and sources and the coarse resolution resolvable by existing ATMs. Figure 2-8a shows the atmospheric “footprint” of a 1 Gt C/yr source, invariant in time and uniform over North America, as calculated using the TM3 ATM (Heimann, 1995). Again, it is clear from the calculation above, together with this figure and the numbers in Table 2-1, that resolving temperate North American fluxes to a few tenths of a Gt C/yr will require measurements of annual mean spatial gradients at a precision of 0.1–0.2 ppm. Table 2-2 lists the observed short-term CO_2 variance from a subset of the CMDL network. For the remote marine boundary-layer continental high-altitude sites, the natural variability is small enough that annual mean gradients of a few tenths of a ppm can be resolved with good interstation consistency of calibrations and other quality control measures. However, because of the high variability of sources and boundary layer mixing over the continents, the annual mean precision at a continental boundary layer station is limited to around 0.4 ppm even with continuous data. The continental measurements shown in Fig. 2-7 illustrate this enhanced variability.

There is a strong need for inverse models with actual winds and accurate boundary layer representations that can use the information contained in this natural variability, rather than treating it as noise. Even at marine boundary layer sites, the inability of models to deal with natural variability is a major limitation. For example, consider two flasks from the Bermuda sampling site, one collected when air was coming directly off of temperate North America and the other when air was coming from over the North Atlantic. Current inverse approaches attempt to distinguish between temperate North American and North Atlantic CO_2 sources using only the average concentration of such flasks. There is obviously much more information contained in the difference in concentration between such flasks, and an approach that could account for synoptic variability and use this information to constrain continental-scale fluxes would be much more powerful.

Table 2-1: Rate of change in integrated vertical column abundance for specific CO_2 sources and sinks.

Source	Assumptions	ppm/day
Los Angeles Basin	12×10^6 people, 4,000 km^2, 1100 mol C/person/day	+10
Netherlands	16×10^6 people, 40,000 km^2, 500 mol C/person/day	+0.6
Germany	83×10^6 people, 350,000 km^2, 580 mol C/person/day	+0.4
Photosynthetic Uptake	Harvard Forest, July	–1.2
U.S. Carbon Sink	1 Gt C/yr, constant in time, uniform over the lower 48 states	–0.08
Southern Oceans	$\Delta pCO_2 = -30\ \mu$atm, wind 15 m/s	–0.06
Eastern Equatorial Pacific	$\Delta pCO_2 = 100\ \mu$atm, wind 7 m/s	+0.04

A second major source of uncertainty in inverse calculations results from the fact that, because of the high CO_2 variability over continents, most of the monitoring stations have been located in the remote marine boundary layer (Fig. 2-2). However, as the footprints in Fig. 2-8 indicate, it is very important to extend the scope of observations to monitor regional CO_2 over the continents in order to quantify fluxes from these regions and link them to specific processes. By comparing the Amazon footprint in Fig. 2-8b to the station locations in Fig. 2-2, it is clear that the existing NOAA/CMDL network observes almost none of this signal. In fact, current inverse calculations must estimate the CO_2 balance of the tropical land biosphere as a residual between fluxes that are estimated in other regions and the global budget, leading to large uncertainties. Furthermore, while some continental footprints do extend out over the oceans, in general these remote signals partly overlap those from other continental-scale regions. For example, a mean difference between the Azores and Barbados could result from either a North American or Eurasian temperate source. Figure 2-9 shows the difference between source footprints from North American and Eurasian boreal sources, as calculated by one ATM (Gloor *et al.*, 1999). The unique elements of these signals are confined almost entirely over the continents. Not surprisingly, the Gloor *et al.* (1999) study found that the number of required stations increased dramatically if they were limited to marine boundary layer locations.

A third source of uncertainty in inverse calculations is systematic error in transport models. Fluxes determined from present inversions are highly model-dependent. Gloor *et al.* (1999) found that inferred SF_6 fluxes varied by a factor of two among 10 different ATMs all inverting the same simulated data on the Globalview network. The magnitude of the North American sink appears to be quite model-dependent (Fan *et al.*, 1998; Rayner *et al.*, 1999; Bousquet *et al.*, 1999), though these differences in magnitude are also influenced by choices in data selection, assumed flux patterns, and presubtracted responses to seasonal biospheric fluxes.

The greatest inconsistency among ATMs is their treatment of vertical

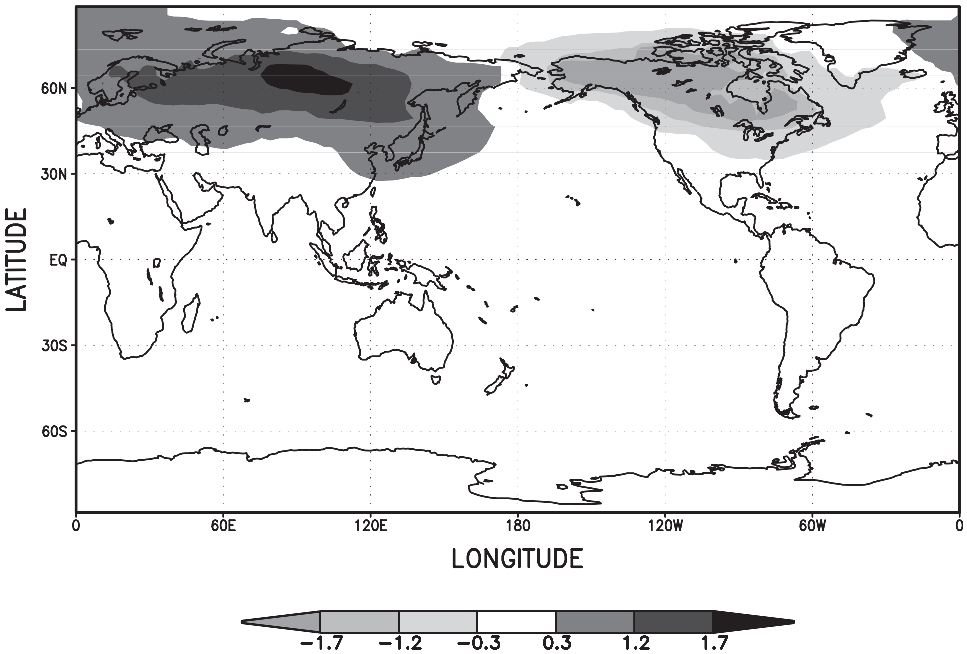

Figure 2-9: Difference between flux footprints, in ppm (Gt C/yr), from Eurasian boreal and North American boreal regions (from Gloor *et al.*, 1999).

mixing through the planetary boundary layer (PBL). This is particularly significant because covariations between mixing and surface fluxes, known as rectifier effects, can produce significant mean CO_2 gradients. For example, during summer when mixing through the PBL is vigorous, the CO_2 deficit due to net biospheric uptake is mitigated by dilution. In contrast, during winter when the PBL is shallow, the CO_2 increase due to net biospheric efflux is enhanced, thus resulting in higher annual-mean CO_2 concentration at the surface and over the continents. The TransCom study showed that rectifier effects produced north-south gradients in 11 ATMs ranging from –1.4 to + 3 ppm, as large or larger than gradients expected from net surface fluxes (Rayner and Law, 1995). Rectifier effects are likely to be just as important to investigating zonal variations in concentrations and fluxes, because of the potential for temporal and vertical variations in atmospheric transport between continents and oceans. Such transport uncertainties must be resolved before inverse calculations can be confidently carried out.

Yet another difficulty associated with the present form of inverse models is the need to prescribe the spatial and temporal patterns of fluxes within each region. Any mismatches between the chosen patterns and the real ones, and particularly interannual variations in the flux patterns, will result in significant model biases. A potential solution to this problem would be to use coupled models that could invert for parameters controlling the underlying processes, rather than for fixed scaling factors.

All of the limitations discussed above become even more significant when trying to invert atmospheric observations to calculate surface fluxes on regional ($\sim 10^6$ km^2) instead of continental scales. Figure 2-10 shows the footprint from a 10^6 km^2 region in the southwestern United States, simulated

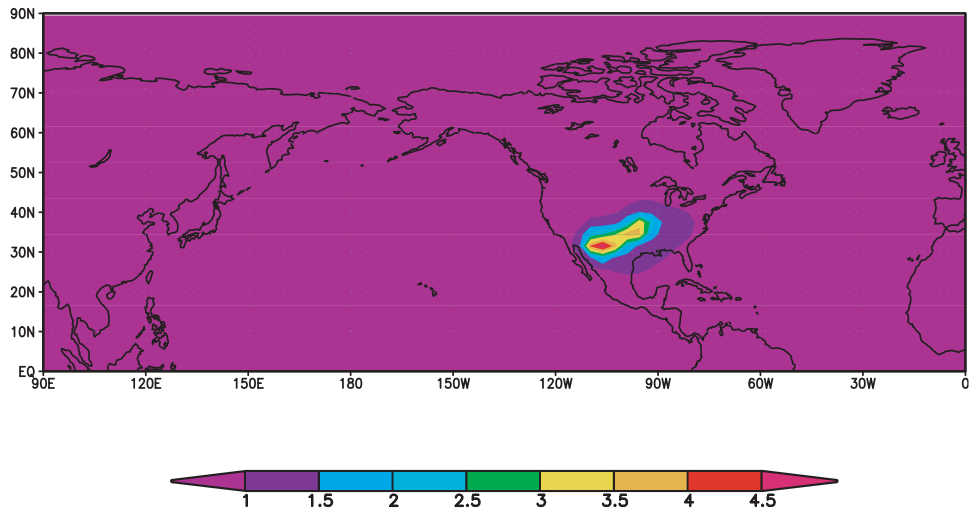

Figure 2-10: Flux footprint, in ppm (Gt C/yr), for a 10^6 km^2 chaparral region in the U.S. Southwest (Gloor *et al.*, 1999).

by an ATM (Gloor *et al.*, 1999). A flux from this region of 0.2 Gt C/yr is predicted to produce measurable annual mean gradients on the order of 0.8 ppm, but on a much smaller spatial scale than those shown for continental-scale regions in Figs. 2-8 and 2-9. Detection of such gradients is also made difficult by the high continental CO_2 variability, which limits annual mean concentration determinations at continental sites to no better than 0.3 ppm (Table 2-2). It appears from Fig. 2-10 and Table 2-2 that a minimum requirement for observing regional fluxes over temperate North America is boundary layer measurements at about 20 sites, and a modeling framework that allows interpreting actual data and synoptic conditions, rather than using monthly or annual means.

Current ATMs, though not perfect, can provide a basis for estimating the most favorable location and nature of our future measurements. The sensitivity tests presented in Addendum 2-2 indicate that reducing the error over temperate North America to 0.2 Gt C/yr is achievable, but will likely require a combination of approaches. Specifically, additional measurements of background CO_2 over South America, Africa, Siberia, the Southern Ocean, and temperate North America, and additional measurements of atmospheric O_2/N_2, $^{13}C/^{12}C$ ratios in atmospheric CO_2, and ocean surface pCO_2 will all advance future atmospheric inverse calculations. If ATMs and inverse methodology can be improved to account for a significant fraction of the high-frequency variability now dealt with as noise, especially at continental sites, this task will be much easier. In that case, the observing system will also be much more fruitful in providing links to process observations, which will improve our understanding of the carbon cycle and predictive capability. An essential element of model improvements is that they be challenged with measurements specifically targeted to test the models' assumptions and performance. These include both intensive measurement campaigns and long-term observations, especially in the vertical dimension.

Table 2-2: Variance in CO_2 observations at selected CMDL sites.

Station Location	Sample frequency	Standard deviation of residuals from smoothed, seasonal curve (ppm)	Estimated standard error of annual mean
South Pole	1/wk	0.1	0.01
Cape Grim	1/wk	0.2	0.03
Samoa	1/wk	0.4	0.06
Cape Kumukahi	1/wk	0.7	0.10
Point Barrow	1/wk	1.1	0.15
Bermuda	1/wk	1.3	0.18
WLEF 400 m	1/day*	3.0	0.26
WITN 500 m	1/day*	4.0	0.35
Baltic Sea	2/wk	4.0	0.40
Mauna Loa	1/wk	0.5	0.07
Niwot Ridge	1/wk	1.0	0.14
Carr 3,000 m	1/wk	1.3	0.18
Carr 6,000 m	1/wk	0.7	0.10
Gobi Desert	1/wk	1.6	0.22

*Assuming two independent measurements per week for conversion to annual mean.

2.3 Recommendations

The overall research objective is to use atmospheric measurements on a space and timescale detailed enough to quantify the effect of all processes, natural and human, that have a major effect on the carbon cycle. This objective corresponds to the first long-term goal of the U.S. Carbon Cycle Science Plan (CCSP, 1999), namely, developing an observational infrastructure and documenting the partitioning among major CO_2 sources and sinks. We make specific recommendations concerning research activities on a timescale of 1 to 5 years, and more general recommendations for the timescale of 6 to 10 years hence.

As discussed above, the existing observational network has contributed greatly to current understanding of the carbon cycle and will provide a critical foundation for expanded measurements in the future. Thus, our first priority is to continue support for these measurements. It is also clear that improving atmospheric constraints on CO_2 fluxes, from the current resolution of broad latitudinal zones to the regional scales that will give process information and prognostic capability, will require significant advances in both the quantity and quality of the measurements. Therefore our second priority is developing a robust and inexpensive in situ CO_2 analyzer to improve the quality of background data by providing measurements independent of potential flask-sampling and analysis biases, and the quantity of data by allowing extensive measurements from aircraft, tall tower, and oceanographic platforms. Our third top priority is improving the quality and comparability of measurements made by various groups to the high levels required for regional- to continental-scale flux determinations.

The observational system that we recommend will have a large numerical modeling component. However, because of the existing sensitivity to high-frequency data variability and systematic atmospheric transport model (ATM) errors discussed earlier, these models must undergo major improvements in terms of their boundary layer representations, and their ability to use assimilated meteorological data and discrete observations, before they can be used to take advantage of the recommended measurements. A more comprehensive modeling goal is to develop carbon cycle models that incorporate known carbon cycle processes, that are capable of incorporating remote-sensing data, that are fully dynamically consistent, and that have resolution high enough to make the confrontation with CO_2 data compelling. These developmental efforts are already underway in several modeling groups.

While we make no specific modeling recommendations in this chapter (see Chapter 5), potential model-data interactions weigh heavily in our choice of recommended measurements. Our second priority level focuses on making intensive and extensive measurements of the vertical and continental distribution of CO_2 that will confront and drive model improvements. The intensive observations will also allow direct flux estimates and column-integrated CO_2 measurements, which can provide valuable process and network-design information independent of improvements to existing ATMs. In our third priority level, we recommend increased measurements of CO_2 and other species in important regions. These last measurements will also be valuable and necessary to achieving our goals, and in some cases their cost-effectiveness may suggest that they be implemented before items higher on the list. We describe the recommendations below, and list them collectively in Table 2-3.

2.3.1 Recommendations for the next 1 to 5 years

Priority Level 1: Improve the quality of existing measurements and support technological development.

1.a. Continue the existing network. The continuation of existing atmospheric measurement programs for CO_2, its isotopic ratios, O_2/N_2, and supporting data, and their interpretation needs to be assured. For CO_2, this includes the airborne profiles recently begun over South America and other regions, as well as modest participation in the Siberian tall tower and aircraft projects currently being implemented by European groups. For O_2/N_2, this recommendation includes tropical stations and shipboard sampling recently and currently being implemented. The data produced from existing atmospheric measurement programs have proved essential to our understanding of the carbon cycle and its development in recent times. Gradually increasing support to counter inflation is necessary to sustain these observations over many years. Also, a modest increase in support is appropriate to achieve the full workup of data as close as possible to its time of collection.

Cost estimate: Currently \$4,000,000 per year (ongoing).

CCSP: Program Element 3.

1.b. Develop and implement a new CO_2 analyzer that is robust, precise, and autonomously operated. The goal is to attain measurement consistency between sites and among laboratories to a level of 0.1 ppm, and to allow extensive measurements on aircraft, tall tower, and oceanographic

Table 2-3: Priorities and cost estimates for atmospheric observation program.

Element of the implementation plan	Priority	One-time Costs	Per-year Costs
Recommendations for the Next 1 to 5 Years			
Improve the quality of existing measurements and support technological development			
Continue existing network	1		$4,000,000
Robust CO_2 analyzer	1	$750,000	$150,000
Quality control and methodology			
CO_2 standards propagation	1		$50,000
Ongoing intercomparisons	1		$225,000
CO_2 isotopic calibration scale	1	$500,000	
$^{13}C/^{12}C$ intercomparisons	1		$100,000
O_2/N_2 intercomparisons	1		$100,000
Make intensive and extensive measurements of the vertical distribution of CO_2 over continents			
Intensive measurements of the North American carbon cycle	2		~$10,000,000 per campaign
Aircraft profiles over continents	2	$3,000,000	$7,000,000
Tall tower observations	2	$2,300,000	$800,000
Make new global measurements of CO_2 and other species			
Background CO_2 measurements	3		$800,000
Measurements on pCO_2 platforms	3		$15,000 per ship
Atmospheric O_2/N_2 measurements	3	$440,000	$240,000
$^{13}C/^{12}C$ and $^{18}O/^{16}O$ measurements	3		$600,000
Robust CO analyzer	3	$850,000	$200,000
Recommendations for the Timescale of 6 to 10 Years			
Increase observations of CO_2, its isotopes, O_2/N_2, and related tracers, and their interpretation for global regional-scale CO_2 flux measurements			
100 new continental sites, 20 commercial ship tracks, and 30 mooring installations.		~$15,000,000	~$15,000,000

platforms (see recommendations for level *2*). An essential feature of quality control is redundancy. The introduction of in situ analyzers in parallel with the traditional flask-sampling effort would catch many potential systematic errors. Flask samples can then also be collected during times of known clean air conditions, improving our ability to relate them to coarse resolution models. The temporal resolution of the data would improve enormously, providing the opportunity to turn a part of the "noise" into signal through use of the appropriate models. Less labor would be required at both the sampling location and the analysis laboratory, thereby decreasing the cost of the entire long-term observing program. This analyzer should be operable by anyone with moderate technical skills, and should be capable of running autonomously for approximately 1 year. The latter requires that the instrument can be calibrated with very small amounts of reference gas. This instrument should be developed by or with close involvement of carbon cycle scientists, but ultimately must be produced in volume by an independent company.

Cost estimate: One-time development, \$350,000; initial production of 10 instruments, \$400,000; operation and data processing, \$150,000 per year.

CCSP: Program Elements 2 and 3.

1.c. Improve quality control and measurement methodology. For logistical, cost, and political reasons, increasing data coverage to support flux estimates can and should be achieved through a truly international effort. Also, because of the quality control value of independent measurements, background measurement efforts in the United States should continue to be shared by multiple government and academic institutions. History shows that the potential for calibration differences and other systematic biases is significant. Gas-handling techniques have to be systematically investigated. The propagation of the WMO Mole Fraction Scale for CO_2 should be improved, and similar common calibration scales should be developed for other species. Ongoing comparisons for CO_2, ^{13}C, and O_2/N_2, between many different laboratories and between different techniques using the same calibration scale, should be instituted as the only acceptable way of making long-term measurements.

Cost estimate: For improved CO_2 standards propagation, \$50,000 per year; for 15 ongoing comparisons (at \$15,000 each), \$225,000 per year; for one-time development of a calibration scale for isotopic ratios of CO_2 in air, \$500,000; for $^{13}C/^{12}C$ intercomparisons, \$100,000 per year; and for O_2/N_2 intercomparisons, \$100,000 per year.

CCSP: Program Element 3.

Priority Level 2: Make intensive and extensive measurements of the vertical distribution of CO_2 over continents.

2.a. Conduct intensive CO_2 measurements to elucidate the North American carbon cycle through a combination of airborne, tower, and ground and ship-based measurements. The purpose of these intensive measurements is to learn how to best measure fluxes on regional scales with an ongoing program, to demonstrate this capability, and to develop the infrastructure to leave in place for a long-term North American observational system. These measurements will address the crucial question of how to scale up from local source estimates, through landscape, regional, and continental to global scales by observing the development and propagation of terrestrial, industrial, and oceanic signals across the continent. They will guide the location of long-term observations such as aircraft profiles and tall towers, and will allow the investigation of potential gaps and sampling biases in these observations such as those due to diurnal, fair-weather, continental, or low-altitude sampling. These intensive campaigns will also provide a wealth of data for testing and improving the next generation of coupled carbon cycle models, which in turn will be able to use these data for network design purposes.

Cost estimate: Approximately $10,000,000 for a month-long campaign (of which $2,000,000 is for aircraft time and rental).

CCSP: Program Elements 2 and 6.

2.b. Repeated vertical profiles by aircraft sampling over continents. In addition to the intensive measurements, ongoing observations of continental CO_2 distributions will be required. The temporal coverage of the intensive measurements will be limited, and many important processes, such as the seasonal rectifier effect, only manifest themselves on longer timescales. Over North America, these measurements must be at a high enough resolution to provide a context for more intensive measurements and to answer the question of how many and what type of continental observations are required for our ongoing network. For these purposes, synoptic-scale coverage of around 25 sites over North America with a sampling frequency of every 2 days is appropriate. This resolution will only be possible using the analyzer recommended in ***1.b.***, but a subset of the flights should include flask samples for purposes of quality control and for measurement of additional tracers. For continental regions other than North America, a few profiling sites will greatly improve the quality of global inverse calculations. At least two aircraft sampling locations over South America, and one each over Africa, and eastern and western Russia are required to fill the largest gaps in global coverage. Aircraft profiles will also be critical for validating future satellite CO_2 systems and ground-based spectrometers, both of which have significant promise for measuring column CO_2 as well as significant potential biases. It would also be highly advantageous to include measurements of CO as a pollution tracer on these flights, if a robust analyzer becomes available (see recommendation ***3.e.***).

Cost estimate: One-time setup costs, $3,000,000 (includes flask units and laboratory instruments); operational costs, $7,000,000 per year (of which $4,000,000 is for aircraft rental).

CCSP: Program Elements 2 and 3.

2.c. Tall tower observations. Aircraft and satellite measurements may suffer from diurnal or fair-weather sampling biases. Continuously operating tall towers can provide critical data at night and in bad weather, and extensive data sets for investigating the interaction between CO_2 fluxes and boundary layer mixing. Species other than CO_2, such as CO (see recommendation ***3.e.***), should be measured for air mass characterization, which will allow an ongoing assessment of sources and sinks over hundreds of kilometers surrounding the tower. A few towers, such as the WLEF tower in Wisconsin, should be selected for a more intensive program involving flux measurements and studies addressing boundary layer mixing, with a full complement of meteorological observations. All of these high-intensity towers will be located in North America, to improve our estimates of temperate North American CO_2 exchange and to leverage numerous other investigations and resources. It is anticipated that investigators in other countries will initiate additional tall tower programs. Vertical extrapolation methods (Potosnak *et al.*, 1999; the "virtual tall tower" concept, K. Davis) should also be pursued as a possible means of obtaining additional information on continental background concentrations.

Cost estimate: One-time setup for 12 towers, \$2,300,000; operational costs, \$800,000 per year.

CCSP: Program Element 3.

Priority Level 3: Make new global measurements of CO_2 and other species.

3.a. Increase classical background CO_2 measurements. It will also be advantageous and relatively inexpensive to augment the amount of marine boundary layer CO_2 data, particularly in currently undersampled regions. Several desert and remote island sites are still potentially useful. The largest gaps in the marine boundary layer network are in the Southern Ocean (Fig. 2-2). Sampling from commercial ships has the potential to significantly increase the background CO_2 data coverage in the Southern Ocean and elsewhere. Atlantic transects would be an important addition to existing Pacific transects. The advantage of using commercial ships is that they cover large distances at relatively high speed and repeat the same tracks regularly. Oceanographic research vessels have the advantage of excellent scientific support, but they generally do not repeat regular transects. Several scientific research and resupply ships do, however, operate on repeated transects. These could easily be used as platforms for atmospheric sampling. Such scientific ships of opportunity include the NOAA Ship *Ka'imimoana*, which conducts repeated transects in the equatorial Pacific in support of the TAO buoy array, and NSF ships making repeated transects between Chile and Palmer Station as well as between Christchurch and McMurdo. Continuous CO_2 measurements should be made on these ships (see recommendation ***3.b.***). Continuous CO_2 measurements should also be made at many of the already existing network sites when new instrumentation is available.

Cost estimate: \$800,000 per year.

CCSP: Program Element 3.

3.b. Background CO_2 measurements on pCO_2 observing platforms. Chapter 3 of this report recommends extensive pCO_2 measurements from a number of oceanographic platforms. In many cases, the instrumentation required to measure pCO_2 will also be suitable for making high-precision background atmospheric CO_2 measurements at the same time. However, such measurements will require additional investments in calibration gases and quality control. The benefits in terms of increased data coverage will be well worth this cost.

Cost estimate: \$15,000 per ship per year.

CCSP: Program Element 3.

3.c. Increased atmospheric O_2/N_2 measurements. The strongest constraint on the long-term terrestrial vs. oceanic flux partitioning comes from measurements of trends in the background O_2 concentration, expressed as deviations in the O_2/N_2 ratio from an arbitrary reference (e.g., Keeling *et al.*, 1996b). In addition, observations of the seasonal cycle in O_2/N_2 provide information on hemispheric oceanic primary productivity and gas-exchange rates, while latitudinal variations in O_2/N_2 are sensitive to the deep overturning circulation of the oceans. There is currently an unresolved discrepancy between the observed north-south atmospheric O_2/N_2 gradient and that predicted by coupled atmosphere-ocean models (Stephens *et al.*, 1998). This discrepancy may be related to how much deep water upwells at low vs. high southern latitudes, and imparts considerable uncertainty into predicted latitudinal CO_2 transports. Additional O_2 measurements are needed in equatorial regions to constrain BOGCMs. More atmospheric O_2 observations are also needed over the Atlantic basin to improve the constraints on Atlantic productivity and the zonal representativeness of the data set. Flask sampling and/or continuous analyzers should be implemented at more background sites and on oceanographic vessels with repeating transects. Airborne measurements are feasible through adaptations to existing technologies, and promise additional insights into marine and continental boundary-layer mixing, as well as a potential means for industrial emission verification.

Cost estimate: One-time setup for three ships and five sites, \$240,000; operational costs, \$240,000 per year; one-time airborne instrument development, \$200,000.

CCSP: Program Elements 2 and 3.

3.d. Measurements of $^{13}C/^{12}C$ and $^{18}O/^{16}O$ fractionation signatures. Measurements of the $^{13}C/^{12}C$ ratio in atmospheric CO_2 provide valuable constraints on the terrestrial vs. oceanic partitioning of the anthropogenic carbon sink, particularly on latitudinal spatial scales and interannual timescales (e.g., Ciais *et al.*, 1995). Additional atmospheric ^{13}C measurements can help elucidate and track the relative contributions of C-3 and C-4 photosynthesis and their isotopic discrimination, which would improve estimates of partitioning between oceanic and terrestrial sources. The oxygen isotopic signatures of CO_2 are influenced differently by photosynthesis and respiration, and thus provide unique information on gross CO_2 exchange rates (e.g., Peylin *et al.*, 1999). The power of ^{13}C and ^{18}O constraints is currently limited by uncertainties regarding the degree of fractionation by various processes and their variability. These isotopic measurements should be done in specific ecosystems and can be integrated with tower studies at several sites.

Cost estimate: \$600,000 per year.

CCSP: Program Element 3.

3.e. Develop a robust CO analyzer. Measurements of atmospheric CO can be very useful in interpreting the influence of industrial emissions on measured CO_2 concentrations. Gas chromatography and other technologies exist that could be adapted into an analyzer that could be included on the routine aircraft and tall tower measurements recommended under priority level ***2*** at a marginal cost. A further benefit of a gas chromatography technique would be additional measurements of CH_4 and H_2.

Cost estimate: One-time development, $350,000; initial production of 10 instruments, $500,000; operation and data processing, $200,000 per year.

CCSP: Program Elements 2 and 3.

2.3.2 Recommendations for the timescale of 6 to 10 years

A number of advances in modeling, technology, and measurement programs are necessary before we can seriously plan the best way to measure regional-scale CO_2 fluxes from the atmosphere. For example, the best combination of methods for determining CO_2 concentrations over a continent will be a tradeoff between the costs of acquiring relatively low-variability data, such as tall tower boundary-layer concentrations or airborne column integrals, and the inverse models' need for such data. If the numerical representation of boundary layer mixing processes advances sufficiently, then either shorter towers or flights with more horizontal and less vertical coverage may be advantageous. Further, if the vertical extrapolation techniques now being considered, such as the "virtual tall tower" concept (K. Davis), prove useful, the instrumenting of existing flux towers may be an alternative to initiating new tall tower or aircraft-profiling sites. The development of satellite or ground-based spectrometric CO_2 sensors will also affect these decisions, and obtaining vertical profiles to test and validate these measurements may take on enhanced priority.

Based on regional-scale flux signatures, such as that shown in Fig. 2-10, we can make several educated guesses as to the resources required by the atmospheric observing system described earlier in this chapter. Thus, we recommend the following.

Increase observations of CO_2, its isotopes, O_2/N_2, and related tracers, and their interpretation for global-wide regional-scale CO_2 flux measurements.

Building on the knowledge gained through the intensive and extensive measurements recommended in priority B, the necessary observations should be implemented to achieve ongoing regional-scale flux resolution over North America and to expand this coverage to the globe. Over North America, a scaling-back from the network put in place in years 1 to 5 may be possible. The chosen network design will likely include about 25 measurement sites (tall tower, airborne, or other) over temperate North America, similar coverage over other continental regions, and atmospheric CO_2 measurements (using the new analyzer recommended in ***1.b***) on commercial ships and mooring networks in every ocean basin. Additionally, a coordinated effort will be required to ensure critical tasks: the synthesis of all available atmospheric and related biogeochemical data; the calculation of regional fluxes and their relationship to regional climate variations and human disturbances; the prediction of future trends in atmospheric CO_2; the assessment of adaptation and mitigation options; and especially, the planning and execution of the necessary measurements (see Chapter 6).

Preliminary cost estimate: For observations at 100 new continental sites, 20 commercial ship tracks, and 30 mooring installations, \$15,000,000 one-time setup, and \$15,000,000 per year.

CCSP: Program Elements 2 and 3.

2.4 Summary

As an entirely independent means of determining surface fluxes, and as top-down checks on fluxes estimated from oceanographic and terrestrial methods, atmospheric observations will continue to play a vital role in our assessments of the global carbon cycle. However, it is clear from the analyses presented here that we can now only perform these calculations with limited spatial resolution. Nonetheless, with a directed effort over the next decade, we can hope to achieve our goal of a robust regional-scale atmospheric observing system. With the set of research activities we recommend for the next 1 to 5 years—continuing our existing measurements, developing a new CO_2 analyzer, improving quality control measures, conducting intensive and extensive measurements of CO_2 over continents, and making focused additions to the observational network—we should be able to measure the overall carbon balance of temperate North America to an accuracy of 0.2 Gt C/yr, while resolving the rest of the globe's continental regions to 0.5 Gt C/yr and major ocean regions to 0.1–0.2 Gt C/yr. This level of resolution will already allow us to test many process-based models, which will be important to predicting the future behavior of the carbon cycle. In addition, by building on what we learn during this initial 5-year phase, we should be able to design and implement an observing system capable of resolving global fluxes on regional (1,000 km) scales, which will improve our understanding of the terrestrial and oceanic biogeochemical processes most important to the carbon cycle.

Addendum 2-1: Sampling and Measurement Biases

Examples of potential sampling biases are shown in Figs. 2-A1 and 2-A2. Figure 2-A1 shows continuous CO_2 measurements at the Mauna Loa Observatory, Hawaii, during July 1998. Clearly visible are low-CO_2 episodes due to upslope winds during the day, when vegetation at lower elevations on the mountain has depleted CO_2 from the air reaching the observatory. The blue dots are hours that meet the selection criteria for background air, which exclude upslope winds but preserve large-scale synoptic variations. Many of the sites in the network have similar potential local effects, but very few have in situ analyzers to help select clean air periods and diagnose potential biases. Another example of challenging local effects is seen in the sampling of air from a platform such as a large container ship. Figure 2-A2 shows a continuous CO_2 record collected by D. Kitzis, with an air intake on one side of the bridge of a ship transiting from Los Angeles to Wellington, New Zealand. There are many pollution spikes from the ship's funnel close to the bridge, but there are also clean air periods. A continuous record provides the option to select clean air episodes, as suggested in the lower panel of this figure, which presents one full day. While pair disagreement in duplicate grab samples usually indicates whether a sample may be contaminated, it is possible that, without the continuous record, a pair of polluted flasks could be equally biased and remain in the database.

At Mauna Loa and several other background sites, independent measurements are made by in situ analyzers and by the collection of air samples in flasks that are analyzed a few weeks later at the Climate Monitoring and Diagnostics Laboratory (CMDL) in Boulder. The results of those analyses for March to May 1998 are compared in Fig. 2-A3a, while Fig. 2-A3b separately plots the difference of each flask value (a flask is filled in 20 s) from the corresponding hourly average measured by the continuous analyzer on Mauna Loa. This comparison cannot be precise because measurement integration

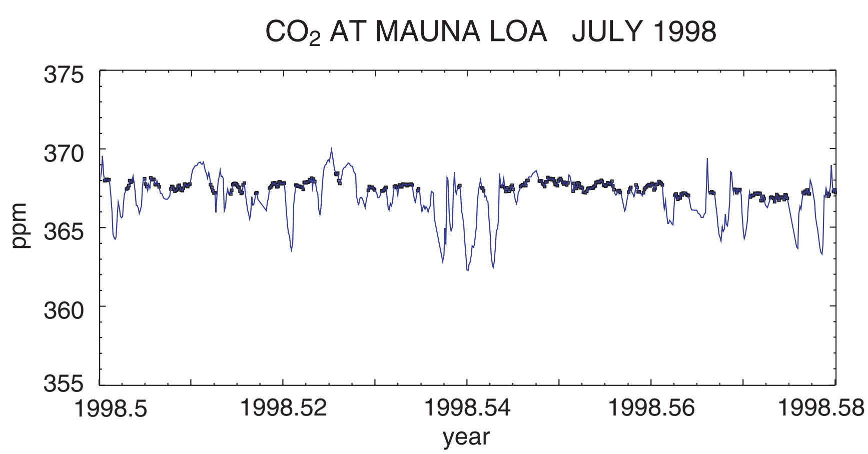

Figure 2-A1: Hourly CO_2 mole fraction observed at the Mauna Loa Observatory, Hawaii, during one month (line), and selected background data (dots).

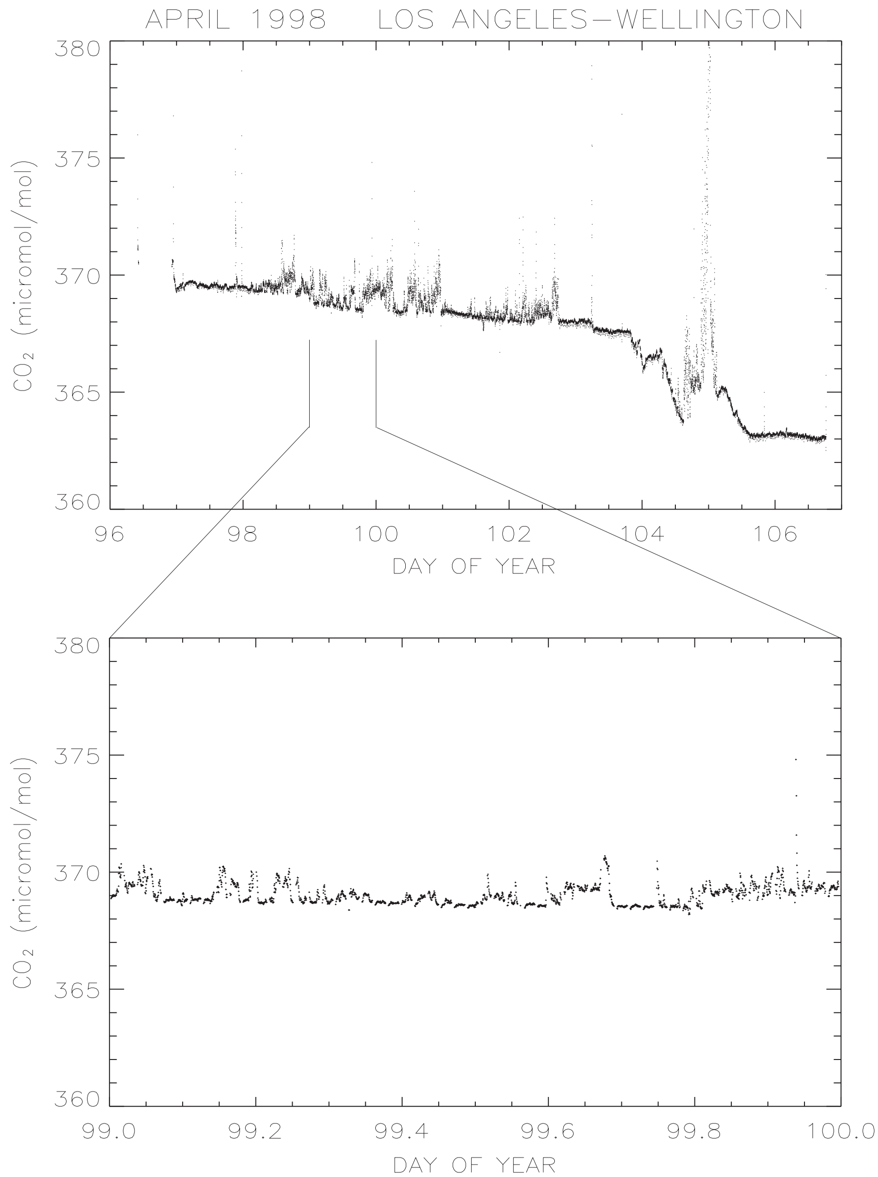

Figure 2-A2: Continuous CO_2 data acquired on a container ship transecting from Los Angeles to Wellington, New Zealand.

times do not match and the air intakes are different. However, persistent offsets of up to 0.3 ppm are indicative of accuracy. These offsets may result from a host of potential problems, such as flask storage effects, analytical errors at CMDL, and analyzer or gas-handling problems at the observatory, but not to inconsistencies between standard reference gases in this case.

A different type of comparison can be made between independent laboratories. The difference of CO_2 monthly mean values (selected for background conditions) at Mauna Loa from 1974 to 1999 between the Scripps Institution of Oceanography and CMDL is 0.20 ppm (1σ). The overall average difference is close to zero, but there are a few extended periods in which the average difference is as large as 0.3 ppm. In this case, the instruments, air

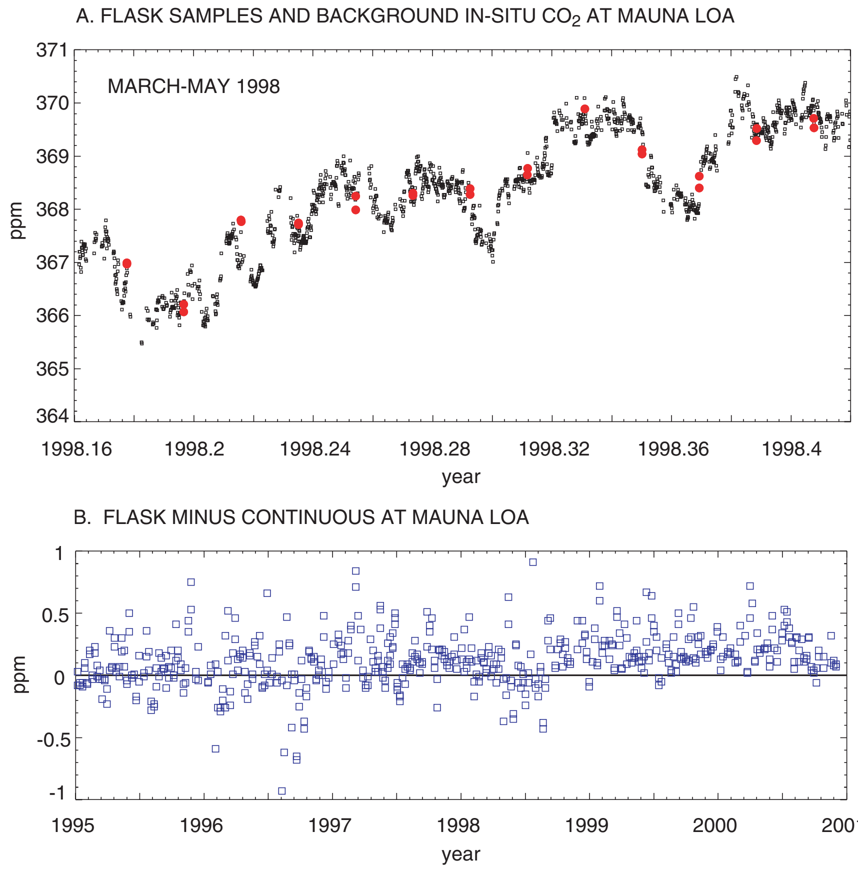

Figure 2-A3: (a) Hourly continuous CO_2 data at Mauna Loa Observatory selected for background conditions (black), and CO_2 in pairs of grab samples in flasks (red). (b) CO_2 mole fraction difference between flask samples and the corresponding hourly average at the Mauna Loa Observatory.

intake lines, data selection, measurement protocol, and reference standards are all different. Since 1992 the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Melbourne, Australia, and CMDL have been comparing measurements in which both laboratories take a sample from the same air. A flask, after filling at Cape Grim, is first analyzed at CSIRO, and then sent on to CMDL for a second analysis. Results are shown in Fig. 2-A4. The agreement is closer than in the case of the comparisons described above, because in this instance the same air is being analyzed. However, the occasional persistent offsets of up to 0.2 ppm are still too large to achieve our stated 5-year goals. As a result of the ongoing intercomparison, analysis problems have been detected and corrected in both labs. Based on our accuracy requirement of 0.1 ppm, and analyses such as those presented in Figs. 2-A3 and 2-A4, we conclude that improving the quality of existing atmospheric CO_2 measurements, through developing and implementing robust in situ analyzers and improved propagation of the calibration scale, must be a high priority in carbon cycle research.

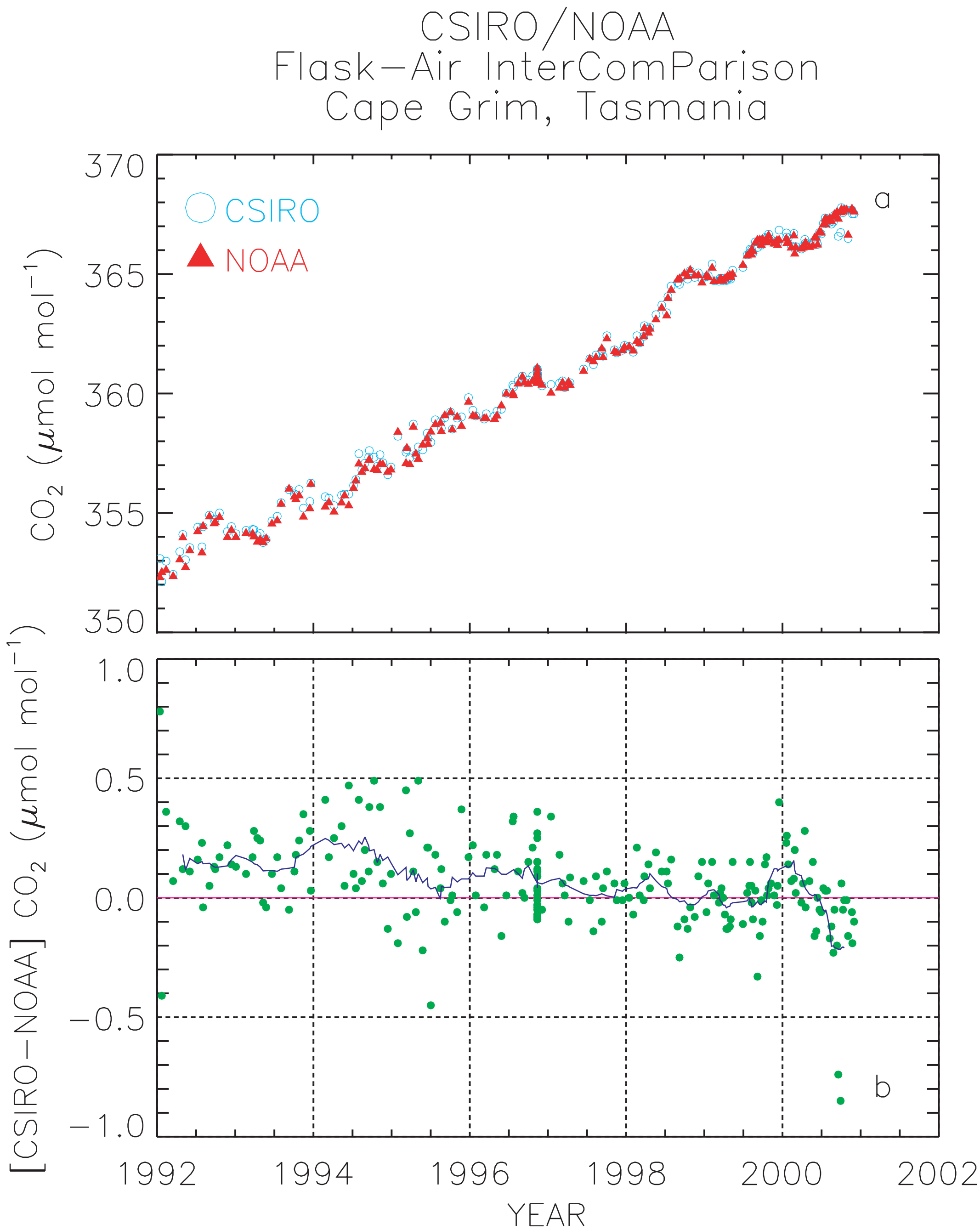

Figure 2-A4: Comparison of CO_2 mole fraction measurements in the same air samples by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and CMDL.

Addendum 2-2: Error Assessments for Enhanced Networks

There are a number of ways to assess uncertainty in inverse flux calculations. One approach starts with a forward ATM run, which is then sampled at specific station locations and times, with an assumed amount of added noise. Depending on the question to be addressed, this added noise can be used to account for the mismatch in time and space between the model predictions and the measured concentrations, or for only the actual measurement error. By inverting these pseudodata with the same ATM, one can derive an estimate of the flux error associated with specific regions and sampling networks. Errors calculated in this way do not reflect the influence of potential systematic biases in the ATM or measurements, and may not reflect the influence of mismatches between the spatial patterns of the true and inverted fluxes (Gloor *et al.*, 1999). Nevertheless, they do contain important information on the contributions of additional measurements in specific locations. We use the annual 17-region synthesis inversion model of Gloor *et al.* (2000), the monthly 14-region assimilation model of Bruhwiler *et al.* (2000), and the monthly 17-region synthesis inversion model of Baker (2000). Table 2-A1 shows the errors these models predict for selected continental-scale regions using surface stations from the existing Globalview network (Globalview-CO_2, 2000). The three inverse models differ considerably in their methodology and temporal/spatial resolution. However, the most significant differences in the sensitivity tests presented here are in the assumed error associated with matching the data and model predictions.

The Gloor *et al.* (2000) study used a relatively conservative noise model, including a subjective assessment of the error associated with current models' inability to represent the high-resolution spatial and temporal variability in the fluxes and atmospheric transport, and the exact location of a station within a model grid cell. The noise models used in the other two studies simply accounted for the error associated with averaging naturally variable data to get monthly means (see footnote to Table 2-A1). The first of these approaches represents a more realistic assessment of what current models can do, whereas the latter indicates the potential of numerical models with moderately improved resolution and accuracy. As discussed below, the development of models that interpreted discrete data rather than monthly or annual means would lead to even further error reductions. Allowing for the relatively higher noise model used by Gloor *et al.* (2000), the three models are generally consistent. As Table 2-A1 shows, the existing network and inverse models can constrain temperate North America to no better than around ±1 Gt C/yr. Allowing for systematic biases in model transport or data would increase this number. As expected, even larger errors are associated with other less constrained regions such as South America and Africa.

Using the spatial information in the Gloor *et al.* (2000) results as a guide, we first ask how much these errors might be reduced by the addition of a tractable number of sampling locations. We divide the addition of these sites into four cases:

Table 2-A1: Annual mean estimation errors for selected regions using surface sites from the Globalview network (in Gt C/yr).

	Gloor *et al.* (2000)[1]	**Bruhwiler *et al.* (2000)**[2]	**Baker (2000)**[3]
Temperate North America	1.1		0.5
North America		0.3	
Temperate Eurasia	2.0		0.4
Eurasia		0.2	
South America	14.0	0.9	2.2
Africa	8.9	1.0	1.0
North Pacific	0.6	0.2	0.2
North Atlantic	0.7	0.3	0.2
Equatorial Pacific	0.8	0.3	0.1
Southern Ocean >55°S	0.4		0.2
Southern Ocean >15°S		0.5	

[1]Using a noise model with approximately 0.7 and 2 ppm random variability on *annual mean* oceanic and continental observations, respectively. From covariance matrix, no prior constraints.

[2]Using a noise model with 0.5 and 2.5 ppm random variability on *monthly* oceanic and continental observations, respectively. Direct comparison of prescribed and retrieved fluxes.

[3]Using a noise model with approximately 0.8 and 1.5 ppm random variability on *monthly* oceanic and continental observations, respectively. From covariance matrix, prior constraints set to ±200 Gt C/yr.

Case 1: Existing tower and airborne sites, including tall towers in Wisconsin and Texas and airborne flask profiles over Colorado, Massachusetts, Hawaii, Alaska, and Rarotonga.

Case 2: Case 1 plus continental sites over South America, Africa, and Eastern and Western Russia, and a commercial ship track from Buenos Aires to Melbourne.

Case 3: Case 2 plus four additional sites over temperate North America.

Case 4: Case 2 plus 10 additional sites over temperate North America.

For the added continental sites, we assume biweekly measurements in the second level of the model, because surface data are likely to be too locally influenced to be useful. Also, mid-boundary-layer concentrations should be measurable by several approaches. The locations of the additional international sites are close to optimized locations found by Gloor *et al.* (2000), and the locations of the additional U.S. sites coincide with existing Ameriflux measurement programs. For the ship track, we assume monthly surface values every 20 degrees of longitude.

Table 2-A2 shows the expected reduction in error for North and South America, Africa, and the North Atlantic and Southern Oceans for these cases. Including the existing tower and airborne site data yields moderate improvements for all the continental regions. Adding the new continental sites and the Southern Ocean ship track greatly improves the South American and African estimates. The addition of proximal sites in Cases 3 and 4

Table 2-A2: Estimation errors for various cumulative network enhancements.

	Gloor *et al.* (2000) (high error estimate)					**Bruhwiler *et al.* (2000) (low error estimate)**				
Region	**TNA**	**SA**	**AF**	**NAO**	**SO**	**NA**	**SA**	**AF**	**NAO**	**SO**
Surface Globalview	1.1	14.0	8.9	0.7	0.4	0.3	0.9	1.0	0.3	0.4
+ existing data aloft	0.9	13.4	8.7	0.7	0.4	0.2	0.7	0.6	0.2	0.4
+ continents + ship	0.8	0.5	1.0	0.6	0.5	0.2	0.3	0.5	0.2	0.2
+ four U.S. sites	0.7	0.5	1.0	0.6	0.5	0.1	0.3	0.5	0.2	0.2
+ six more U.S. sites	0.6	0.5	1.0	0.6	0.5	0.1	0.3	0.4	0.2	0.2

TNA = temperate North America, SA = South America, AF = Africa, NAO = North Atlantic, SO = Southern Ocean, NA = North America

continues to improve the temperate North American estimates. The Bruhwiler *et al.* (2000) model, with a relatively lower noise model, suggests that the network represented by Case 2 is theoretically capable of providing our desired constraints. However, these sensitivity tests do not allow for systematic biases in modeled transport or measured concentrations, either or both of which could be significant. The higher observational errors assumed by Gloor *et al.* (2000) provide a more realistic estimate of our potential flux constraints using existing models, and indicate that further data enhancements beyond Case 4 may still be necessary.

Alternatively, by taking a very different approach to the inversion of atmospheric data, it may be possible to invert using actual measurements rather than either annual or monthly means. This approach would require high-resolution meteorological models that could define influence functions individually for every measurement in the data set. The inversion would then be performed on these influence functions rather than on the annual or monthly mean response functions as is currently done (M. Gloor, personal communication; S. Denning, personal communication). If such an approach were successful, then the uncertainty now associated with averaging records with high variability (see Table 2-2) would diminish.

While we don't have a model to test this explicitly, we can get some idea of the potential improvements by setting the assumed error over the continents to a similar low value as over the oceans, an admittedly optimistic scenario. Applying this potential improvement in the Bruhwiler *et al.* (2000) model reduces error by a factor of four for the temperate North American flux estimates (not shown in tables). An important additional benefit of using actual data rather than means would be the improved detection of carbon flux anomalies in the region surrounding the observation site. The flux anomalies could be matched with climate variations, thus improving the understanding of relevant processes. While this large error reduction is promising, model improvements will take some time and may never reach the level of noise reduction we assume above. Their short-term success may depend on how much of the high-frequency variability (see Fig. 2-7b) is due to synoptic transport, which we can presently model, and how much is due to local-flux and boundary-layer interactions, which we cannot presently model.

Continental-scale atmospheric inversions can also benefit from additional a priori constraints on various regions. For example, atmospheric O_2/N_2 and ^{13}C measurements provide constraints on the annual mean global partitioning of terrestrial versus oceanic CO_2 sources (Battle *et al.*, 2000; Manning, 2001). With moderate enhancements to the O_2/N_2 and ^{13}C observational networks, and improvements in understanding their budgets, we might be able to constrain the global annual mean partitioning of CO_2 uptake between land biosphere and oceans to within 0.5 Gt C or better. By comparison, the error on this partitioning using the Bruhwiler *et al.* (2000) model, as shown in Tables 2-A1 and 2-A2, is 1.3 Gt C/yr for the enhanced Case 4. Thus, applying an a priori constraint based on O_2/N_2 and ^{13}C data can further improve the continental-scale estimates (Rayner *et al.*, 1999).

Oceanic measurements of pCO_2 and other quantities constrain air-sea CO_2 fluxes for specific ocean basins. It may be possible to constrain the annual mean CO_2 flux for continental-scale ocean regions to within 0.1–0.2 Gt C by significantly extending oceanic pCO_2 coverage and improving estimates of gas exchange rates (see Chapter 3 of this report). Including these air-sea flux constraints in an inversion will lead to improved estimates of terrestrial fluxes. Using the Gloor *et al.* (2000) model, we find that knowing fluxes for ocean regions to within 0.2 Gt C/yr reduces the estimation error on temperate North America by 0.3 Gt C/yr using the surface Globalview sites, and by 0.1 Gt C/yr for Case 4 above. Finally, these inverse models can be used to assess the sensitivity of our flux determinations to systematic interlaboratory biases (e.g., Fig. 2-A4). Because laboratories tend to focus measurements in their own regions of the world, such biases could lead to significant errors in flux estimates. Artificially offsetting the measurements over North America by 0.5 ppm resulted in a 0.7 Gt C/yr error over temperate North America for our enhanced Case 4 when using the Bruhwiler *et al.* (2000) inversion model. The Gloor *et al.* (2000) model shows a similar sensitivity, with an artificial increase of 0.2 ppm over North America, resulting in a 0.2 Gt C/yr error over temperate North America. Thus both models support our approximate estimate for a continental-scale flux-response ratio of 1 ppm/(Gt C/yr). However, if only marine boundary layer stations are used, the signals for a given flux are much smaller. These sensitivities highlight the need for tight interlaboratory comparisons and frequent maintenance of the traceability of reference gas standards.